Reprinted from JOURNAL OF THE OPTICAL SOCIETY OF AMERICA, Vol. 55, No. 9, 1068–1072, September 1965
Printed in U. S. A.

Effect of Stimulus Duration on the Perception of Red–Green and Yellow–Blue Mixtures*

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(Received 12 April 1965)

Thresholds for the perception of red and green or for blue and yellow, presented in two-color mixtures, were measured at exposure durations of 20, 50, 100, and 300 msec at the fovea and 6° above the fovea, at a constant luminance of 0.12 ft-L. Median foveal thresholds for red and green were constant from 300 to 50 msec and decreased slightly at 20 msec; at 6°, sensitivity to both red and green declined with decreasing exposure time. Median thresholds for blue deteriorated as exposure time decreased from 300 to 100 msec, but improved with further reductions in stimulus duration. The median yellow thresholds declined as exposure time was reduced below 100 msec. The results are compared with previous data obtained as a function of retinal position and luminance and with similar thresholds measured under conditions of constant brightness. The results are also discussed in relation to various estimates of the "risetimes" of different colors.

PREVIOUS studies have investigated the effects of size, retinal position, and luminance on two-color mixtures.[1–6] Stimulus duration would be expected to be another important variable. If, as has been reported,[7–9] there are differences in the time required for a light stimulus to exert its maximum effect—its "risetime"—as a function of wavelength, then the threshold for each color in a two-color mixture should presumably vary as a function of the relative risetimes of the two components.

In this study, thresholds for red and green or for blue and yellow, presented in two-color mixtures, have been measured for various exposure durations at two retinal positions. Since the risetimes reported in previous studies[7–9] range from about 20 to 260 msec, we have used exposure durations of 20 to 300 msec.

APPARATUS

The apparatus and procedure have been described in detail in previous papers.[4,5] Briefly, the stimuli were mixtures of either red and green or blue and yellow, provided by sets of narrow-band interference and sharp-cutoff filters. These are described in Table I. The two component wavelengths were mixed in one-half of the bipartite field of a MacAdam colorimeter[10] and presented as a circular stimulus 1° in diam. The stimulus luminance was kept constant at 0.12 ft-L at all mixture proportions. The surround was a matte, white screen illuminated to 0.06 ft-L by a Macbeth daylight lamp of approximately equal energy distribution.

A disk shutter with various-sized openings and rotated by a constant-speed motor and clutch assembly, controlled the stimulus exposure time. The presentation of the stimulus was controlled by the experimenter.

PROCEDURE

Thresholds for the perception of either red and green or blue and yellow were measured with the method of constant stimuli at two retinal positions (fovea and 6° above the fovea) and four exposure times (20, 50, 100, and 300 msec). For either mixture, the stimulus generally appeared white or gray with the proper amounts of the two components, although at times the red–green mixture appeared yellow. At other values the first mixture usually appeared either red or green and the second mixture appeared either blue or yellow. Thresholds were measured in both directions from the neutral point. The observer's task was to report whether or not a given color could be perceived in a mixture; the percent seen of the designated color was plotted as a function of the photopic luminance ratio of the two colors in the mixture. Sensitivity was measured by the luminance ratio, either red/green or yellow/blue. For example, an increasing yellow/blue ratio reflects either impaired sensitivity to blue or improved sensitivity to yellow, or both.

There were at least three sessions at each condition; if the variability was high, additional sessions were run until the points plotted on a cumulative normal frequency distribution described a straight line.[4]

TABLE I. Description of stimulus components.

Filter	Dominant wavelength (mμ)	Percent purity	Half-width (mμ)
Red	650	70	16
Green	499	80	12
Yellow	574.5	99.5	16
Blue	478	84.5	21

* From Bureau of Medicine and Surgery, Navy Department, Research task MR005.14-1001.01. The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the U. S. Navy Department or the Naval Service at large.

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In the first experiment, red–green mixtures were presented. Because changing the shutter opening to regulate exposure time was awkward and time consuming, only one exposure time was presented during a session, and exposure time was randomized between sessions. Both colors were measured at the two retinal positions during each session.

In the second experiment, in which yellow–blue mixtures were presented, a way was found of changing the shutter opening quickly, and it became feasible to present the four exposure times randomly during each session. Therefore, the retinal positions were randomized between sessions and thresholds for one color, either yellow or blue, were obtained in each session.

The observers were adapted to the surround luminance for 4 min at the start of each session. All observations were monocular, with the left eye occluded. Five color-normal members of the laboratory staff served as observers. Three were highly experienced in this type of experiment, and two (PK and BR) were not.

RESULTS

Red–Green

Thresholds for red and green in terms of red/green luminance ratios are given for all observers in Table II; the median thresholds are plotted in Fig. 1. The median was chosen rather than the mean because of the failure to obtain threshold values under some conditions, even with a stimulus of maximum purity.

Median thresholds at the fovea for both red and green show very little change at the various exposure times. They drop very slightly as time decreases from 300 to 50 msec and somewhat more sharply with a further decrease to 20 msec, the green a little more than the red.

Table II. Luminance ratios of red–green mixtures needed for the perception of red or green.

		Fovea				6°			
		Red		Green		Red		Green	
Time (msec)	O	Limen	σ	Limen	σ	Limen	σ	Limen	σ
20	JK	0.37	0.04	0.27	0.03	1.60	0.78	0.18	0.28
	HM	0.41	0.02	0.33	0.08	1.03	0.17	a	a
	PK	1.15	0.08	a	a	2.15	0.60	a	a
	BR	0.38	0.04	0.34	0.04	0.54	0.11	0.42	0.21
	SW	0.52	0.06	0.39	0.05	1.33	0.25	a	a
50	JK	0.41	0.04	0.32	0.02	1.13	0.10	0.40	0.05
	HM	0.44	0.04	0.40	0.02	1.13	0.19	0.10	0.20
	PK	0.43	0.03	0.45	0.02	1.05	0.25	0.05	0.05
	BR	0.42	0.05	0.43	0.05	0.84	0.10	0.49	0.09
	SW	0.58	0.06	0.43	0.02	1.20	0.18	a	a
100	JK	0.42	0.02	0.31	0.03	1.00	0.14	0.52	0.11
	HM	0.46	0.03	0.38	0.02	1.06	0.08	0.15	0.13
	PK	0.43	0.03	0.44	0.02	0.99	0.07	0.35	0.15
	BR	0.21	0.16	0.43	0.06	0.71	0.15	0.57	0.12
	SW	0.65	0.04	0.45	0.02	0.99	1.00	a	a
300	JK	0.44	0.02	0.33	0.02	0.94	0.06	0.60	0.04
	HM	0.46	0.05	0.44	0.05	0.95	0.07	0.55	0.10
	PK	0.43	0.02	0.43	0.02	0.83	0.13	0.62	0.09
	BR	0.18	0.18	0.42	0.04	0.74	0.06	0.62	0.10
	SW	0.59	0.02	0.48	0.02	0.94	0.08	0.10	0.15

[a] Threshold could not be obtained even with a stimulus of maximum purity.

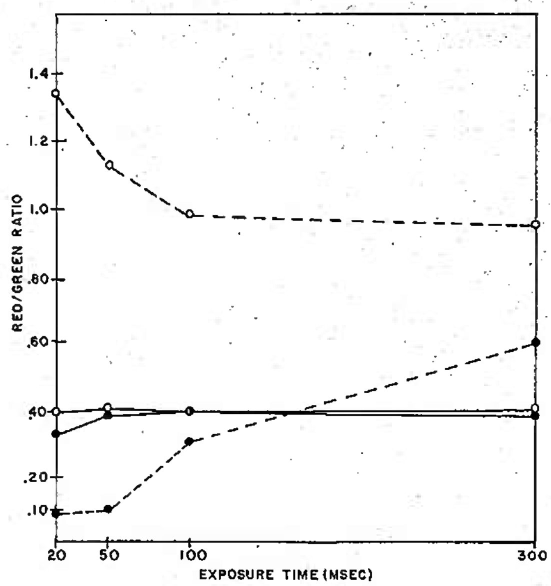

Fig. 1. Median luminance ratios of red–green mixtures needed for the perception of red and green at four exposure times in the fovea and 6° above the fovea. Foveal red ○——○, 6° red ○- - -○, foveal green●——●, 6° green ●- - -●.

Almost no individual variation is found in the foveal curves, except for PK; at 20 msec, his red threshold rose sharply, and no green threshold could be measured, even with a green stimulus of maximum purity.[11]

At 6°, median thresholds for the perception of red rise as exposure time decreases, while those for the perception of green drop. All the individual red curves increased slightly as exposure time was decreased from 200 to 50 msec. With a further decrease to 20 msec, however, the ratios increased still more for three observers and decreased for two of them. All the individual green curves showed a decrement with decreasing exposure time, and at 20 msec no thresholds could be obtained for three of the observers with a stimulus of maximum purity.

Comparing foveal and peripheral results, we note that the red/green ratios required for the perception of red are larger at 6° at all exposure times, but the ratios needed for the perception of green are larger at 6° only at 300 msec; at shorter durations they are larger in the fovea. In general, there is a large difference between the foveal

[11] The curves for BR are also somewhat anomalous in that his red thresholds are lower at 300 and 100 msec than at 50 or 20 msec; but since they are also lower than the respective green thresholds (indicating more green light in the red thresholds than in the green threshold itself), he may have been having criterion difficulties. He, in fact, reported that at the longer durations he almost always saw a red spot surrounded by a green annulus rather than the usual gray or yellow. It is conceivable, then, that his criterion for green was the smallest possible annulus around a predominantly red field while the criterion for red was the smallest red field in the center of the green annulus. At shorter exposures, or in the periphery, such a subtle judgment may have been impossible, forcing him to judge only the general impression of color.

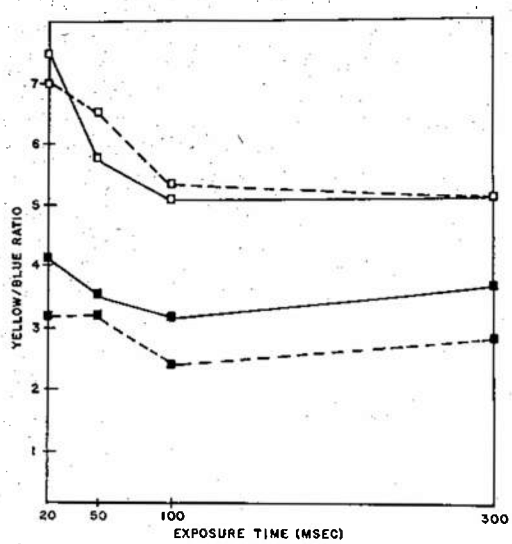

FIG. 2. Median luminance ratios of yellow–blue mixtures needed for the perception of yellow and blue at four exposure times in the fovea and 6° above the fovea. Foveal yellow □——□, 6° yellow □– – –□, foveal blue ■——■, 6° blue ■– – –■.

and peripheral ratios required for the perception of both red and green, although the size of the difference changes with exposure time.

Foveal variability did not increase appreciably with decreasing exposure time, and peripheral variability increased only at 20 msec. Variability of the peripheral thresholds was greater than that of the foveal thresholds at all exposure times.

Blue–Yellow

The threshold ratios for blue and yellow for all observers are given in Table III and the median thresholds are plotted in Fig. 2. Median yellow curves for both the fovea and 6° show little change from 300 to 100 msec; below that duration, they rise steadily. This finding reflects the general trend of the individual curves except for SW whose foveal yellow curve drops with decreasing exposure time. The individual peripheral yellow curves generally rise as exposure time is reduced, except for the decrease between 50 and 20 msec for PK.

The median blue curves for both the fovea and 6° drop from 300 to 100 msec and then rise as duration is further decreased. The changes in the individual foveal blue curves are small, except that the curve for PK rises sharply at 20 msec. The shapes of the peripheral blue curves are not consistent between observers, but they all share the characteristic that the curve is never at its lowest point at 300 msec.

Comparing the foveal and peripheral results, foveal yellow/blue ratios are generally slightly lower for perception of yellow and higher for the perception of blue at all exposure times. The few exceptions in the individual data must be considered in the light of the very small differences between the foveal and peripheral ratios for the perception of both blue and yellow in contrast with the large foveal–peripheral differences for red and green. The differences between the median foveal and peripheral yellow/blue ratios remain relatively constant at all exposure times, again in contrast to the red/green results.

Both foveal and peripheral variability increased rather steadily with decreasing exposure time, and again peripheral variability was greater than foveal variability.

DISCUSSION

Figures 1–3 show that, by and large, the changes in sensitivity to two-color mixtures presented for different durations are quite small. This is particularly true in view of the sizable losses in brightness which occur at 20 msec. Such constancy of color perception in the face of variable brightness has been noted before for stimuli of constant duration.[5,6]

Although the changes in the ratios are small, they are reliable and generally consistent among observers. One possible explanation for the changes is that there is a loss of sensitivity to each color with decreasing exposure time, partly as a result of the dimming of the stimulus. This would result, for example, in a continual increase in the red/green ratios needed for the perception of red and a decrease needed for the perception of green. This is evident in the results for the periphery. Similarly, there was a sizable increase in the yellow/blue ratios needed to perceive yellow at 20 msec. The one observer who did not require an increased yellow/blue ratio at 20 msec (SW) reported that there was no sizable decrease in the brightness of the yellow stimulus.

To test the possibility that the changes are due to the dimming of the stimulus, threshold ratios were again

TABLE III. Luminance ratios of yellow–blue mixtures needed for the perception of yellow or blue.

		Fovea				6°			
		Yellow		Blue		Yellow		Blue	
Time (msec)	O	Limen	σ	Limen	σ	Limen	σ	Limen	σ
20	JK	6.20	4.44	2.40	0.40	[a]	[a]	3.20	0.74
	HM	8.00	4.15	4.65	0.90	6.60	2.25	4.65	0.88
	PK	[a]	[a]	7.10	1.60	4.00	4.00	3.10	0.80
	BR	7.50	3.00	2.00	0.50	7.00	3.00	2.05	0.95
	SW	4.80	1.40	4.10	0.50	8.90	8.45	3.50	1.50
50	JK	5.80	1.10	2.85	0.45	7.20	1.90	3.20	0.63
	HM	5.20	0.80	4.70	1.10	5.60	2.25	4.45	0.60
	PK	8.30	2.50	5.40	1.00	5.50	2.50	4.60	1.20
	BR	6.50	3.50	2.45	0.35	6.30	3.00	2.20	0.55
	SW	4.30	1.30	3.60	0.60	8.40	7.30	1.45	2.00
100	JK	5.10	0.80	2.80	0.25	5.25	0.50	2.50	0.84
	HM	4.40	0.80	4.10	0.55	5.00	2.10	3.75	1.05
	PK	5.80	2.30	5.00	0.40	5.30	1.60	4.70	0.50
	BR	4.80	0.70	2.90	0.30	6.10	1.80	2.30	1.00
	SW	5.20	0.90	3.30	0.30	6.60	2.40	1.60	0.60
300	JK	5.10	0.80	2.70	0.30	4.90	0.30	2.85	0.68
	HM	5.40	0.90	4.20	0.35	5.50	1.20	3.90	0.95
	PK	4.90	1.30	5.00	0.70	4.50	1.40	4.30	0.50
	BR	4.80	0.60	2.51	0.30	5.00	1.10	2.90	0.45
	SW	5.60	0.55	3.85	0.50	6.20	1.75	2.60	0.80

[a] Threshold could not be obtained even with a stimulus of maximum purity.

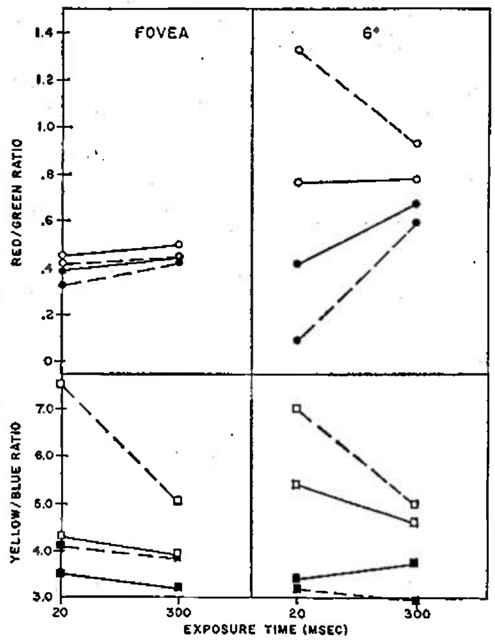

FIG. 3. Median luminance ratios of red–green and yellow–blue mixtures needed for the perception of these colors at 20 and 300 msec in the fovea and 6° above the fovea for stimuli both of equal energy (– – –) and equal brightness (——). Red ○, green ●, yellow □, and blue ■.

measured foveally and peripherally, at 300 and 20 msec, but the brightnesses of the stimuli were equated at the two exposure times. The procedure was as follows: Threshold ratios were first obtained at 300 msec, either foveally or peripherally, and the brightness of the surround was equated to the stimulus. Then the proportions of the mixture were adjusted until the observer perceived the color in question at a 20-msec exposure, with the stimulus still equal in brightness to the surround. Thus, a somewhat crude method of adjustment, rather than the method of constant stimuli, was used to measure the thresholds. The individual luminances needed to equate the 20-msec to the 300-msec stimulus are given in Table IV.

The results of the procedure are compared with the original thresholds in Fig. 3. There has been virtually no change in the relative foveal red/green ratios. The slight changes that have occurred can probably be attributed to the difference in method. The relationship of the foveal blue thresholds remains unchanged, but there has been a large reduction in the size of the ratio for yellow at 20 msec.

In the periphery, the sharp rise in the red/green ratio needed for the perception of red when brightness was not constant has disappeared, but there is still a sizable drop in the ratio needed for the perception of green. There has been little change in the yellow function but an apparent reversal in the blue function; when brightness is kept constant, the ratio drops slightly at 20 msec.

Despite this improvement in the stability of the ratios when brightness is held constant, certain changes still occur reliably for and among most observers.

It is possible, then, that these changes reflect differences in the relative efficiency of the various wavelengths at a given exposure time, resulting from different risetimes. Unfortunately, there is lack of agreement as to the relative risetimes of the various wavelengths, or whether there are differences at all.[12,13] Assuming, however, that the changes result primarily from differences in risetimes, the present data would indicate that the relative effectiveness of red and green are roughly parallel in the fovea and periphery down to 20 msec, when red is somewhat more effective. Relative efficiency of yellow and blue, on the other hand, while much the same at both retinal positions, is not parallel. The median results (Fig. 2) show that blue is more effective at 20 msec, and thus has a faster risetime than yellow.

Despite the fact that the most recent study dealing specifically with risetimes of different wavelengths concludes that wavelength has no effective perceptual latency,[13] our analysis generally conforms to the original finding of Broca and Sulzer[7] as well as to the recent findings of Kinney. Using some of our observers in a series of studies dealing with chromatic induction, she concluded that blue has a faster risetime than yellow[14] and that blue is more effective as an inducing field at short durations.[15]

The present results, at 300 msec, also confirm previous data obtained with a 1-sec exposure.[5,6] In all cases a shift from the fovea to 6° in the periphery resulted in little change in the yellow/blue ratios; on the other hand, the red/green ratios increased at 6° indicating impaired sensitivity to red or improved sensitivity to green.

There have been reports of marked adaptation to chromatic stimuli, even with very short exposure times. Broca and Sulzer[16] found it to be most marked for blue stimuli, and Clarke[17] has noted that the effect is particularly significant in the periphery. We have also found a decrease in the yellow/blue ratio needed for the perception of blue and an increase in the ratio needed for the perception of yellow as the session progressed.

TABLE IV. Average luminance in ft-L of the yellow–blue mixtures at an exposure time of 20 msec equated in brightness to the 300-msec exposures at a luminance of 0.12 ft-L.

Observer	Fovea	6°
JK	0.36	0.32
HM	0.31	0.24
PK	0.27	0.26
BR	0.22	0.19
SW	0.24	0.23

[12] W. H. Stainton, J. Opt. Soc. Am. 18, 26 (1928).
[13] S. L. Guth, Vision Res. 4, 567 (1964).
[14] J. A. S. Kinney, J. Opt. Soc. Am. 55, 738 (1965).
[15] J. A. S. Kinney, J. Opt. Soc. Am. 55, 731 (1965).
[16] See Ref. 7, p. 978.
[17] F. J. J. Clarke, Opt. Acta 7, 355 (1960).

This phenomenon was much less marked in the fovea than in the periphery, but it occurred even with dark-adapted observers.

The present study also confirmed previous reports of confusion in color naming under other adverse conditions.[18] Our observers typically reported that with short exposures green stimuli even at maximum purity appeared blue, and yellow stimuli appeared red.

[18] R. M. Boynton, W. Schafer, and M. Neun, Science 146, 666 (1964).